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COOLING OF A DOUBLE-ROW RADIAL ENGINE BY WATER INJECTION TO THE INDIVIDUAL CYLINDERS

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NACA

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

COOLING OF A DOUBLE-ROW RADIAL ENGINE BY WATER INJECTION TO THE INDIVIDUAL CYLINDERS

By Louis L. Monroe and Harold E. Friedman

SUMMARY

An injection system that supplies water to each cylinder of a double-row radial engine was tested in the Cleveland altitude wind tunnel as part of a general investigation of the power-plant installation of a four-engine heavy bomber. The tests were conducted to determine the effectiveness of water injection in cooling the engine during take-off. A method of injection was devised by means of which the same quantity of water could be metered to each of the engine cylinders.

The injection of 500 pounds of water at the take-off power condition reduced the maximum measured exhaust-valve-seat temperature 64° F and the maximum spark-plug-gasket temperature 55° F. Flight tests of this method of injection resulted in cylinder-head temperature reductions similar to those obtained in the wind tunnel. These reductions were more uniform than those obtained with a system in which water was injected ahead of the engine-driven supercharger.

INTRODUCTION

Cooling difficulties were encountered with the four-engine heavy bomber during take-off under Army summer air conditions, particularly at high gross weights when long take-off and transition runs were required. The cylinder-head temperature limits specified by the manufacturer for the double-row radial engine in the bomber were reached during ground running prior to take-off and were exceeded in the take-off. Inasmuch as operation at temperatures that exceeded the specified limits resulted in engine failures owing to warping of the exhaust-valve seats, additional cooling was needed at this critical condition. Cooling by means of water would probably most adequately provide the required reduction in temperature.

The results of water-injection tests conducted in the Cleveland altitude wind tunnel as a part of an extensive investigation of the bomber power-plant installation requested by the Army Air Forces, Air Technical Service Command, are reported herein. The injection system tested was designed to meter an equal quantity of water to all cylinders by the injection of water through a nozzle inserted in the primer hole of each cylinder. Uniformity in metering was necessary inasmuch as the hottest cylinders varied with engine power and with different double-row radial engines.

Flight tests were also conducted on the four-engine heavy bomber by the Boeing Aircraft Company at Seattle in order to check the wind-tunnel test results.

DESCRIPTION OF APPARATUS

The wind-tunnel installation of the engine in the right inboard nacelle is shown in figure 1. The engine (fig. 2) is an 18-cylinder, double-row, radial engine with a normal rating of 2000 brake horsepower at an engine speed of 2400 rpm and a take-off rating of 2200 brake horsepower at an engine speed of 2600 rpm. The engine is equipped with a single-stage gear-driven supercharger, two turbosuperchargers, and a four-bladed propeller. The propeller is 16 feet and 7 inches in diameter and rotates at 0.35 engine speed.

NACA Individual-Cylinder Water-Injection System

The NACA individual-cylinder water-injection system used in the wind-tunnel tests consisted of a distribution manifold extending around the periphery of the engine, nozzles inserted in the primer holes of each cylinder, and medium-pressure aircraft hoses connecting nozzles to the manifold. The installation of the system on the engine in the airplane nacelle is shown in figures 3 and 4 and the method of injection into the intake-valve primer port of a cylinder is shown in figure 5.

The circular water-distribution manifold (fig. 6) was fabricated from four segements of 1-inch outside-diameter stainless-steel tubing. The nozzles were made from short lengths of 1/8-inch outside-diameter tubing silver-soldered into aircraft fittings as shown in figure 7. All of the nozzle orifices were 0.0225 inch in diameter except the orifice in cylinder 18, which was 0.031 inch in diameter. A front-row and a rear-row hose and nozzle assembly are shown in figure 8.

Instrumentation

Cylinder-head temperatures were measured on all cylinders with standard rear-spark-plug-gasket thermocouples. Exhaust-valve-seat and exhaust-valve-guide temperatures were also measured on several representative cylinders. As shown in figure 9, the exhaust-valve-seat thermocouple was located approximately 1/8 inch from the valve-seat face and 1/8 inch from the wall of the combustion chamber on a line joining the centers of the exhaust valve and the rear spark plug. The exhaust-valve-guide thermocouple touched the guide bushing approximately 1/2 inch from the bottom of the guide (fig. 9). The cooling-air temperatures were measured by two thermocouples in the cowl inlet. All temperatures were recorded on self-balancing potentiometers.

Fuel flow and water flow were measured by calibrated rotameters. The fuel used throughout the tests conformed to specification AN-F-28 (grade 100/130). The brake horsepower was determined by means of a torquemeter furnished with the engine.

TESTS AND METHODS

The water-injection tests were made at normal rated and take-off powers for a range of cowl-flap deflections at water-injection rates of 0, 285, 335, and 500 pounds per hour. Comparative tests were made with and without water injection at approximately the same air temperature, pressure altitude, airspeed, engine conditions, and cowl-flap deflection in order to permit direct comparisons. Data were recorded without water injection after all test conditions had stabilized; water was then injected and data were recorded after conditions had again stabilized.

Simulated take-off runs with and without water injection were also conducted by idling the engine at a speed of 1000 rpm until cylinder-head temperatures stabilized and then accelerating the engine to take-off power in 10 seconds. A summary of test conditions is given in table I.

RESULTS AND DISCUSSION

Stabilized Conditions

All cylinder temperatures were adjusted to a reference ambient temperature at the cowl inlet by applying a correction of 1° F for each degree Fahrenheit variation of the cowl-inlet air from the reference temperature. The cooling-air temperatures of the tests in which no water was injected were arbitrarily selected as the reference temperatures. The corrections to the cylinder-head temperatures never exceeded 7° F.

The effects of individual-cylinder water injection on the cylinder-head temperatures measured at exhaust-valve guides, rear spark-plug gaskets, and exhaust-valve seats are shown in figures 10 and 11 for take-off and normal rated power, respectively. The greatest temperature reductions occurred at the exhaust-valve seats. These reductions varied for the different cylinders from 64° to 102° F with a water-injection flow of 500 pounds per hour at take-off power conditions. (See fig. 10.) The average value of the three exhaust-valve-seat temperatures measured was reduced 88° F. At normal rated power with a water-injection flow of 285 pounds per hour, temperature reductions at the exhaust-valve seats varied from 52° to 82° F. (See fig. 11.) The hottest rear-spark-plug-gasket temperatures were reduced 55° F at take-off power and 36° F at normal rated power. The effect of water injection on the exhaust-valve-guide temperature was similar to that of reference 1 in which water injection did not reduce the exhaust-valve-guide temperature.

The temperature-reductions obtained with individual-cylinder water injection were fairly uniform for all cylinders at conditions of both take-off and normal rated power despite the dissimilarity of the temperature patterns for the two conditions. (See figs. 10 and 11.) This uniform reduction in temperatures indicated reasonably uniform water flow to all cylinders and also indicated that the water distribution was not greatly influenced by the engine power conditions. Because of the uniform water distribution, it is believed that individual-cylinder water injection, in addition to cooling the power plant at take-off, can be extended for use at war-emergency power ratings.

When water was added, the reductions in the maximum and average rear-spark-plug-gasket temperatures were approximately the same, as shown for two power conditions in figure 12. The temperature spread with and without water injection was approximately 32° F at take-off power and approximately 58° F at normal rated power.

A few tests were made to compare the effectiveness of the cowl flaps with and without water injection. Cowl-flap effectiveness $\Delta T/\delta_f$ is defined as the change in cylinder-head temperature for a unit change in cowl-flap deflection. The results, shown in figure 13, indicated that the cowl flaps were equally effective with and without water injection.

During several tests a few injection nozzles clogged because of dirt or chips in the water system. Fouling of the nozzles may be avoided by using adequate filtering equipment to prevent dirt or foreign matter from entering the water lines or nozzles.

Simulated Take-Off Conditions

The results of the simulated take-off runs at take-off power for a 3-minute period are presented in figure 14. The 3-minute period chosen represents a reasonable time for a take-off and transition run. The tests indicated that, after 3 minutes without water injection, the rear-spark-plug-gasket temperatures had risen 40° F and were still steadily rising. With water injection, however, the temperatures rose for approximately 50 seconds then dropped. At the end of 3 minutes with a water-injection flow of 500 pounds per hour, rear-spark-plug-gasket temperatures were 55° F lower when corrected to the same initial conditions than they would have been without water injection. The tunnel airspeeds at which these tests were conducted also are given in figure 14.

Application to Flight

In order to check the results of the individual-cylinder water-injection tests obtained in the Cleveland altitude wind tunnel, flight tests were conducted at Seattle on a four-engine heavy bomber by the manufacturer. (See reference 2.) Injection nozzles with 0.025-inch-diameter orifices were installed in all cylinders. A summary of the flight-test conditions is given in table II.

Stabilized temperature tests were made similar to those conducted in the wind tunnel. Take-off and climb tests were also made with and without water injection.

Incidental to the tests of the individual-cylinder water-injection system, a comparison was made with another system, in which water was injected into the diffuser just ahead of the engine-driven supercharger and distributed to the cylinders with the fuel and charge-air mixture. This method will be referred to as "supercharger-inlet injection."

The flight-test results showing the effects of NACA individual-cylinder water injection and supercharger-inlet injection on rear-spark-plug-gasket temperatures are presented in figures 15 to 17 for take-off and normal rated powers. The results are in agreement with wind-tunnel test results. At take-off power and an engine speed of 2600 rpm (fig. 15), the maximum rear-spark-plug-gasket temperature was reduced 78° F in the flight tests with the NACA system as compared with 55° F in the wind-tunnel tests; however, approximately 10 percent more water was used in flight.

The results of supercharger-inlet injection tests were not so satisfactory as those with individual-cylinder water injection. At take-off power the maximum rear-spark-plug-gasket temperature was reduced only 36° F with supercharger-inlet injection as compared with 78° F with the NACA individual-cylinder system (fig. 15).

The temperature reductions obtained with supercharger-inlet injection were not uniform. At take-off power, as shown in figure 15, supercharger-inlet injection decreased the temperature of some cylinders only a few degrees, whereas others were reduced approximately 75° F. The data in figures 15 to 17 have been replotted in figures 18 to 20 in order to compare the maximum, average, and minimum temperature reductions obtained for the two injection systems. The minimum temperature reduction obtained at take-off power with individual-cylinder water injection was 62° F and the maximum reduction was 90° F, a spread of 28° F. (See fig. 18(a).) The minimum temperature reduction obtained with supercharger-inlet injection was 6° F and the maximum reduction was 90° F, a spread of 84° F. Similarly, the spreads were 26° F and 75° F at take-off power at an engine speed of 2800 rpm and 40° F and 70° F at normal rated power for the individual-cylinder and supercharger-inlet injections, respectively (figs. 19 and 20). These results indicate appreciably better water distribution to the different cylinders when using the NACA individual-cylinder injection system than when using the supercharger-inlet injection system.

The variation in maximum rear-spark-plug-gasket temperature without individual-cylinder water injection and with water injected at the rate of approximately 500 pounds per hour is given in figures 21 and 22 for two take-off and climb tests. The maximum temperature after a 1/2-hour steady climb at take-off power was 101° F lower than in a test in which no water was added. (See fig. 21.) Similarly, for a steady climb to 30,000 feet at normal rated power (fig. 22), the maximum temperature with water injection was 92° F lower than in a climb in which no water was added.

SUMMARY OF RESULTS

The following results were obtained from tests of a water-injection system on a double-row radial engine in a four-engine heavy bomber:

1. Engine-cylinder temperatures were greatly reduced by water injection through the intake-valve primer holes of each cylinder. At take-off power, the maximum rear-spark-plug-gasket temperature was reduced approximately 55° F with a water-injection flow of 500 pounds per hour and the maximum exhaust-valve-seat temperature measured was reduced approximately 64° F.

2. Temperature reductions obtained with NACA individual-cylinder water injection were fairly uniform for all cylinders.

3. Results of flight tests of the individual-cylinder water-injection system showed close agreement with the results of wind-tunnel tests and demonstrated the practicability of the installation in the airplane if adequate precaution is taken during installation to prevent fouling of the injection nozzles.

4. A comparison of the results of two water-injection systems tested indicated that greater and considerably more uniform cylinder-head-temperature reductions were obtained with the individual-cylinder water-injection system than with a system in which water was injected into the diffuser just ahead of the engine-driven supercharger.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 27, 1945.

REFERENCES

1. Rothrock, Addison M., Krsek, Alois, Jr., and Jones, Anthony W.: Summary Report on the Induction of Water to the Inlet Air As a Means of Internal Cooling in Aircraft Engine Cylinders. NACA ARR, Aug. 1942.

2. Hopkins, Joseph D.: Flight Test of B-29 Engine Cooling with Several Water Injection Systems. Model XB-29. Rep. No. D-6107, Boeing Aircraft Co., Dec. 30, 1944.

TABLE I - SUMMARY OF CONDITIONS FOR ALTITUDE-WIND-TUNNEL TESTS OF

FOUR-ENGINE HEAVY BOMBER POWER-PLANT INSTALLATION

Data in figure	Engine speed (rpm)	Brake mean effective pressure (lb/sq in.)	Brake horsepower	Manifold absolute pressure (in. Hg)	Total fuel flow (lb/hr)	Specific fuel consumption (lb/bhp-hr)	Fuel-air ratio	Cowl-flap deflection (deg)	Tunnel pressure altitude (ft)	Free stream dynamic pressure (lb/sq ft)	Water injection rate (lb/hr)	Cowl-inlet temperature (°F)
10	2600	200	2200	50.0	1700	0.773	0.106	12.0	4000	31.1	0	34
10	2600	200	2200	50.0	1700	.773	.106	12.0	4000	31.1	500	37
11	2400	197	2000	45.4	1450	.725	.103	12.0	4000	38.7	0	37
11	2400	197	2000	45.5	1450	.725	.103	12.0	4000	39.6	285	36
13	2600	200	2200	50.0	1700	.773	.106	12.0	4000	30.7	0	40
13	2600	200	2200	50.0	1700	.773	.106	12.0	4000	31.0	335	38
13	2600	200	2200	50.0	1700	.773	.106	16.0	4000	30.6	0	33
13	2600	200	2200	50.0	1700	.773	.106	16.0	4000	30.5	335	33
13	2600	200	2200	50.0	1700	.773	.106	26.0	4000	30.4	0	35
13	2600	200	2200	50.0	1700	.773	.106	26.0	4000	30.9	335	37
14	2600	200	2200	50.0	1680	.773	.106	12.0	4600	35.0	0	69
14	2600	200	2200	50.0	1690	.773	.106	12.0	4600	34.0	335	74
14	2600	200	2200	50.0	1690	.773	.106	12.0	4600	33.0	500	80

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TABLE II - SUMMARY OF CONDITIONS FOR FLIGHT TESTS ON FOUR-ENGINE HEAVY

BOMBER, LEFT INBOARD ENGINE, MADE BY BOEING AIRCRAFT COMPANY

Data in figure	Engine speed (rpm)	Brake mean effective pressure (lb/sq in.)	Brake horsepower	Manifold absolute pressure (in. Hg)	Total fuel flow (lb/hr)	Specific fuel consumption (lb/bhp-hr)	Fuel air ratio	Cowl-flap deflection (deg)	Altitude (ft)	Water-injection rate (lb/hr)	Indicated airspeed (mph)	Outside air temperature (°F)	Water-injection system
15	2620	201	2230	47.8	1675	0.752	0.103	12.0	5700	0	196	56.0	Off
15	2625	202	2240	49.4	1740	.777	.106	12.0	5710	540	196	56.0	NACA
15	2610	200	2210	48.7	1770	.802	.110	12.0	5725	420	196	56.5	S.I.[a]
16	2810	186	2210	48.1	1725	.781	.107	12.0	5700	0	196	55.0	Off
16	2810	188	2230	49.7	1810	.812	.111	12.0	5830	500	196	56.0	NACA
16	2810	187	2230	48.9	1820	.820	.112	12.0	5710	420	197	57.0	S.I.[a]
17	2400	197	2000	44.3	1480	.740	.105	12.0	5715	0	197	51.0	Off
17	2410	197	2010	44.5	1530	.762	.108	12.0	5715	464	196	52.5	NACA
17	2415	197	2015	44.8	1550	.769	.108	12.0	5605	390	197	57.0	S.I.[a]

[a] Supercharger-inlet injection

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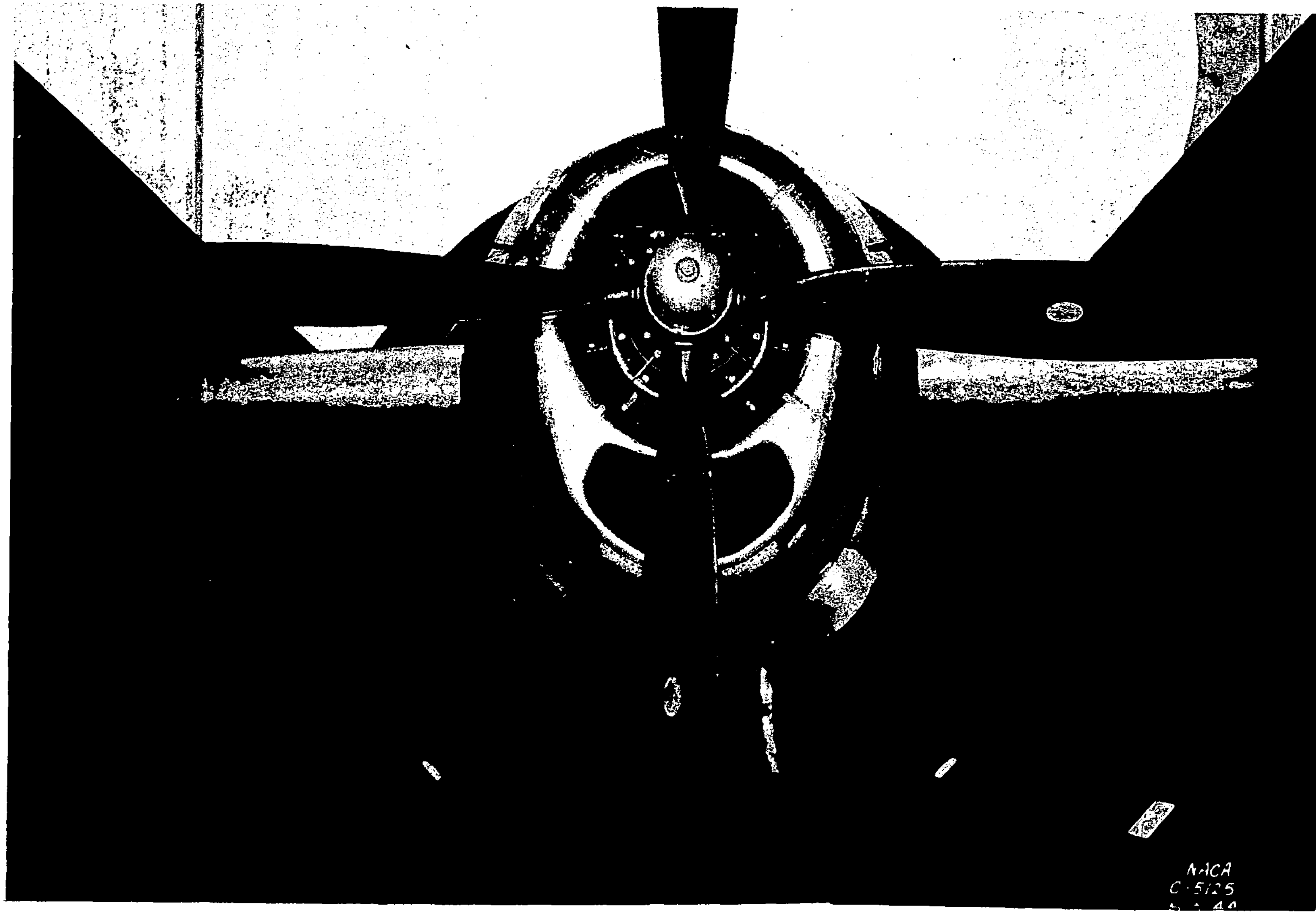


Figure 1. - Front view of altitude-wind-tunnel installation of double-row radial engine in right inboard nacelle. Production configuration.

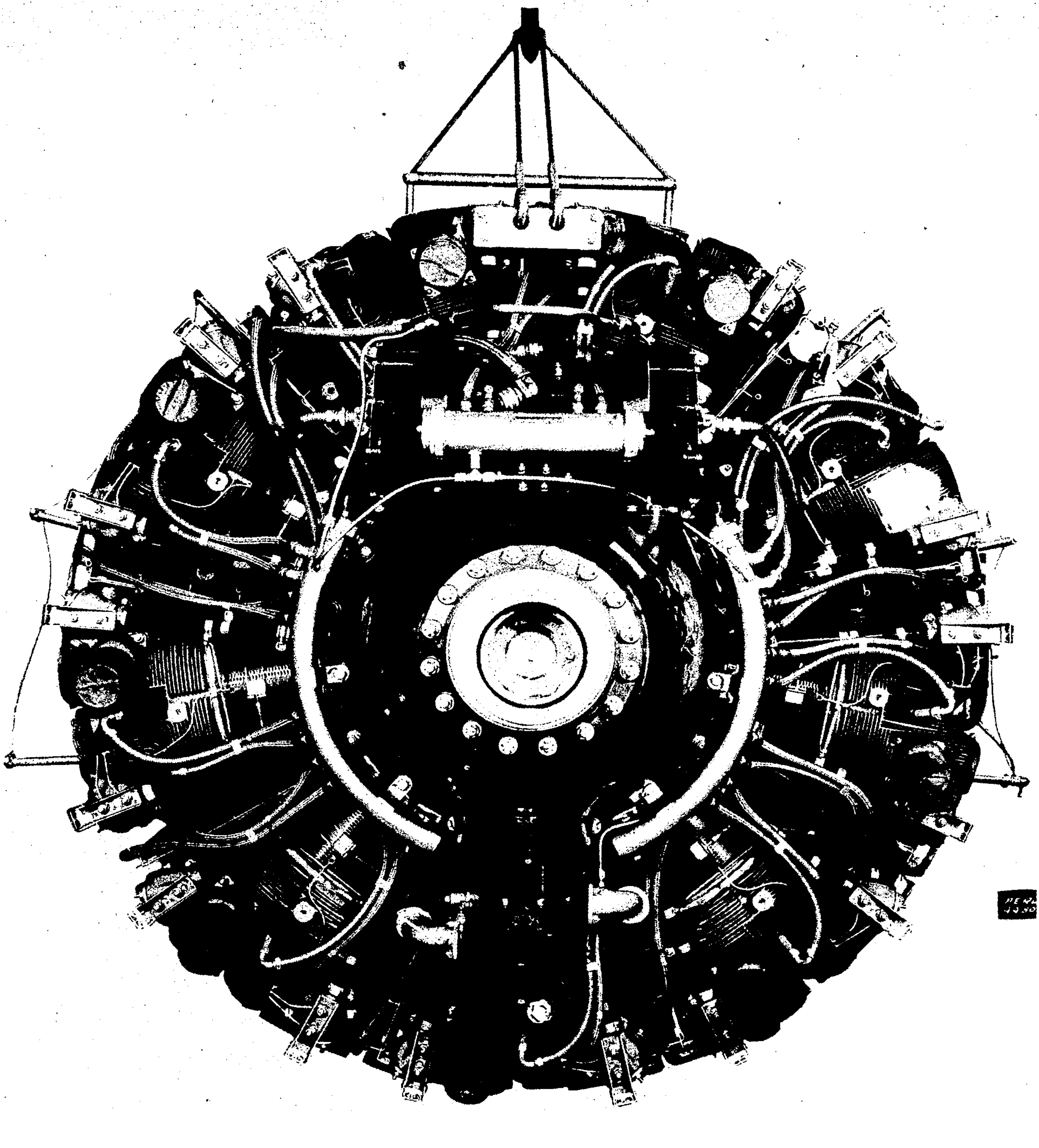


Figure 2. - Front view of double-row radial engine.

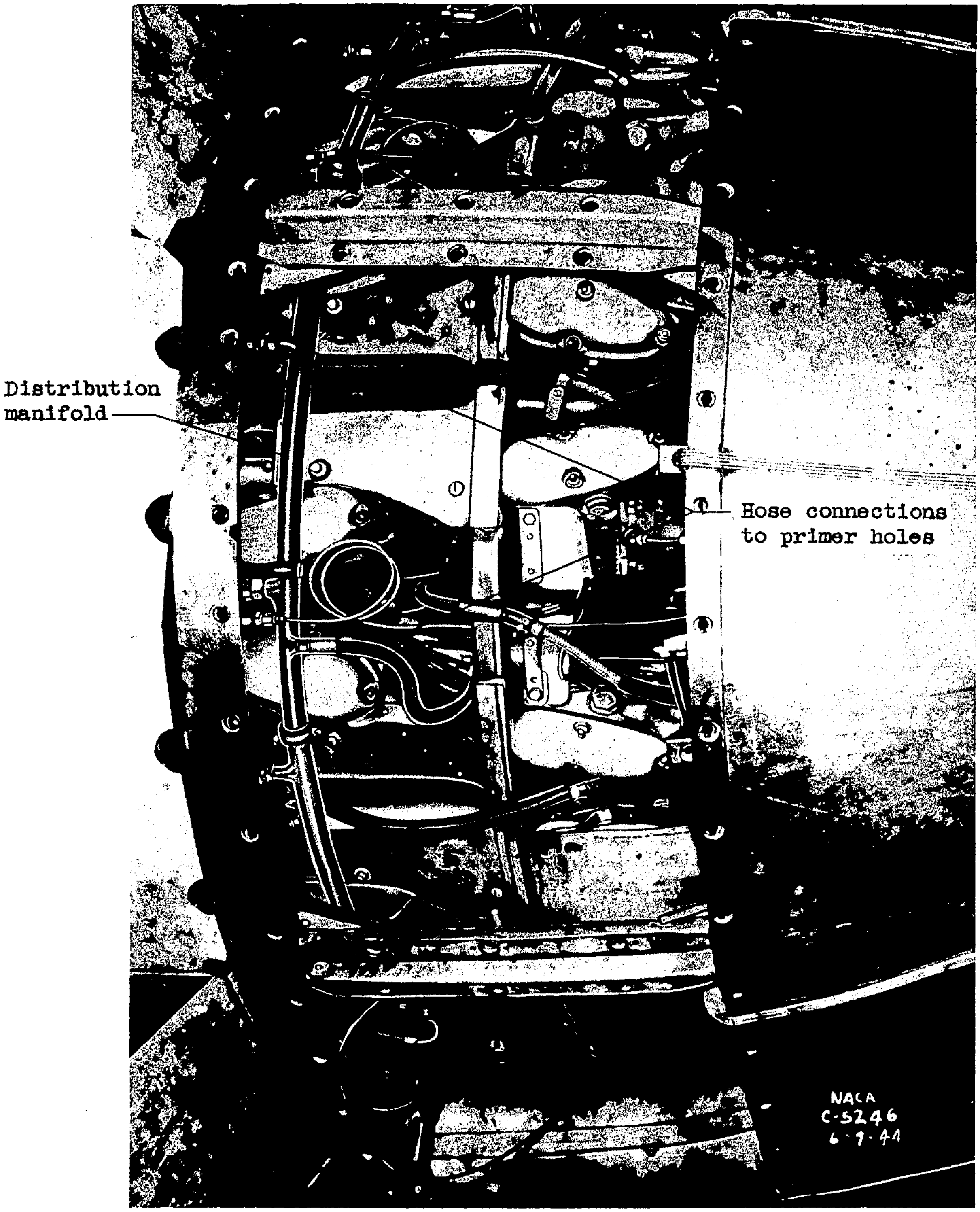


Figure 3. - Installation of water-distribution manifold and connections on double-row radial engine in nacelle for NACA individual-cylinder water-injection system.

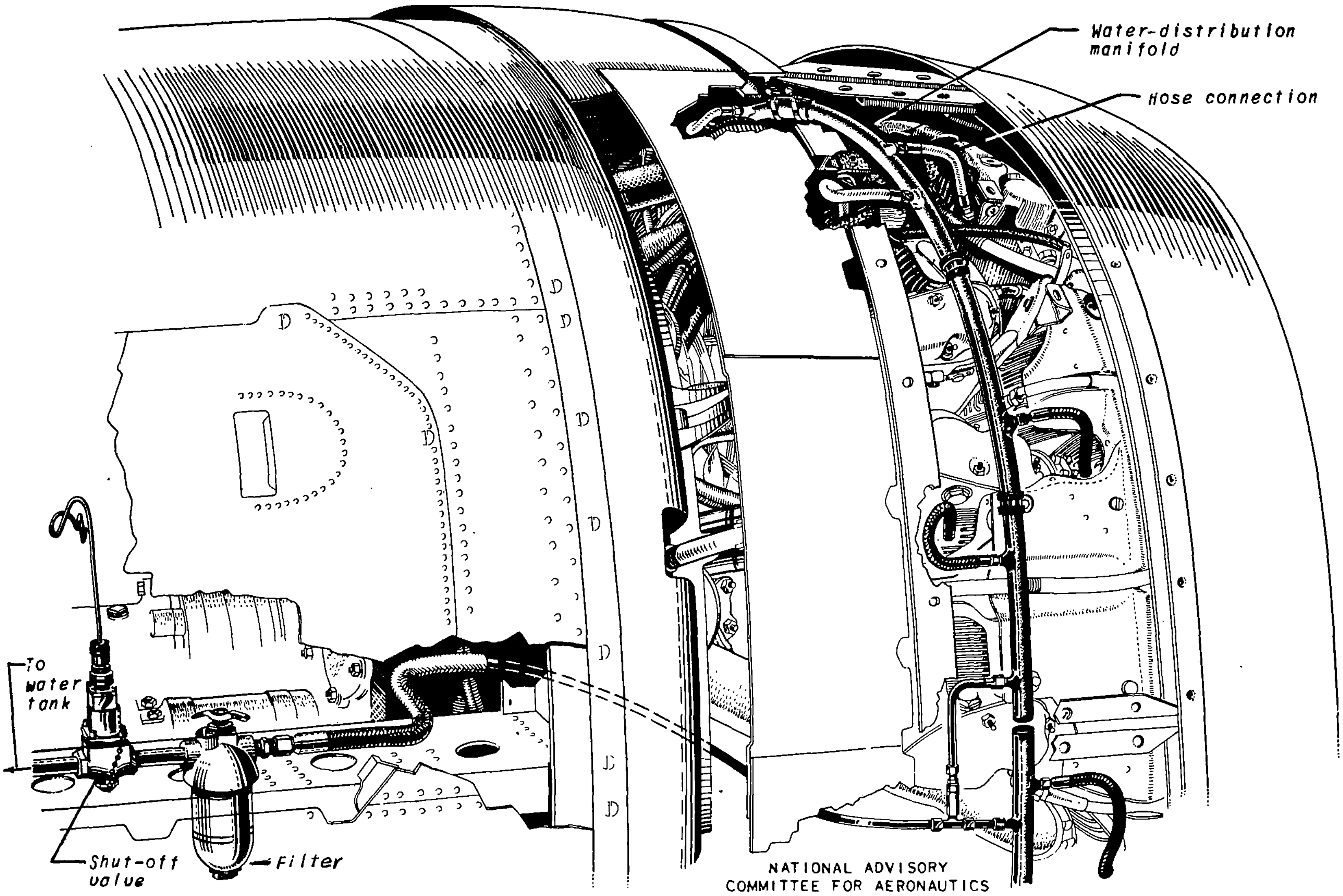
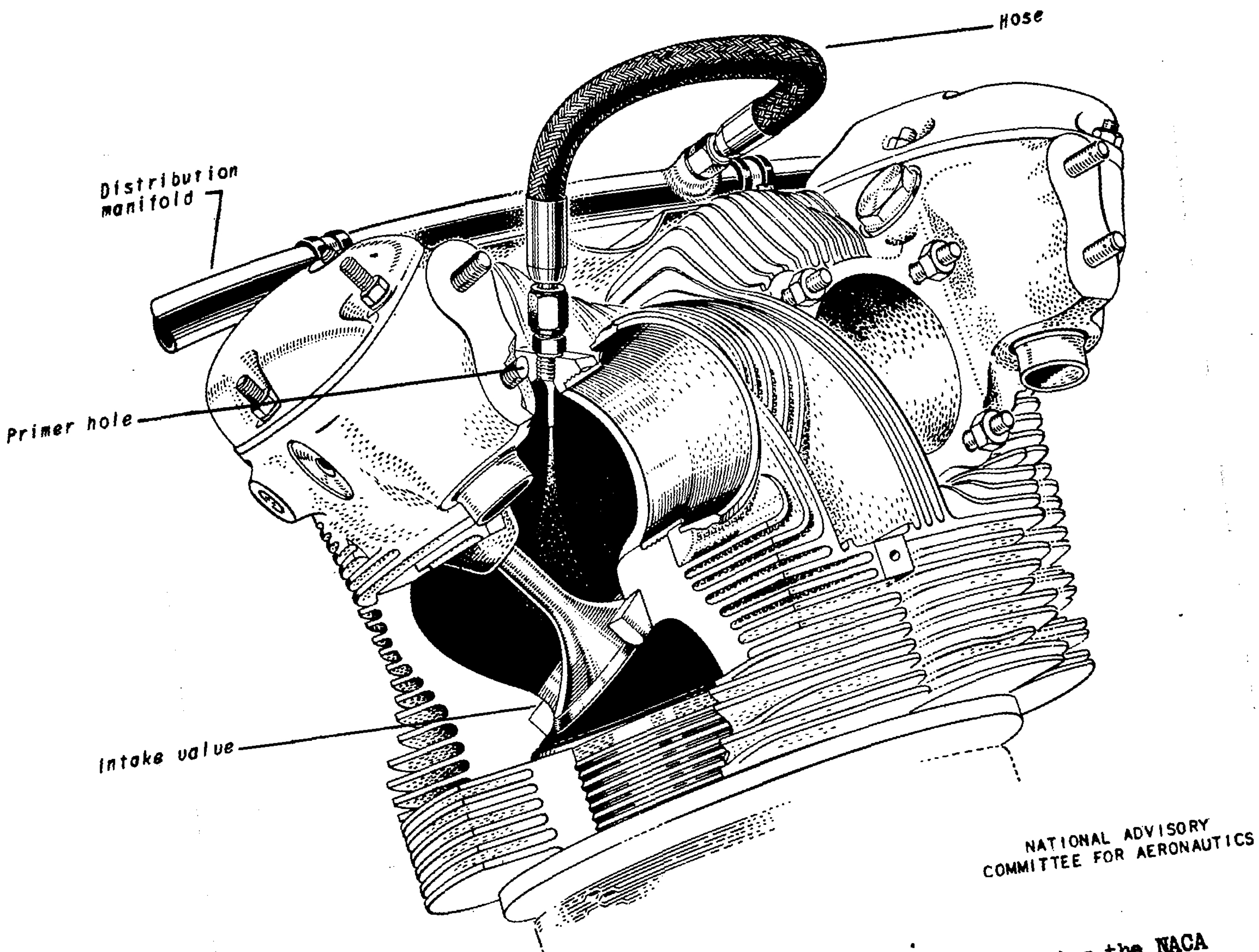


Figure 4. - Installation of NACA individual-cylinder water-injection system on double-row radial engine in four-engine heavy bomber.



... view of double-row radial engine cylinder showing the NACA ... system.

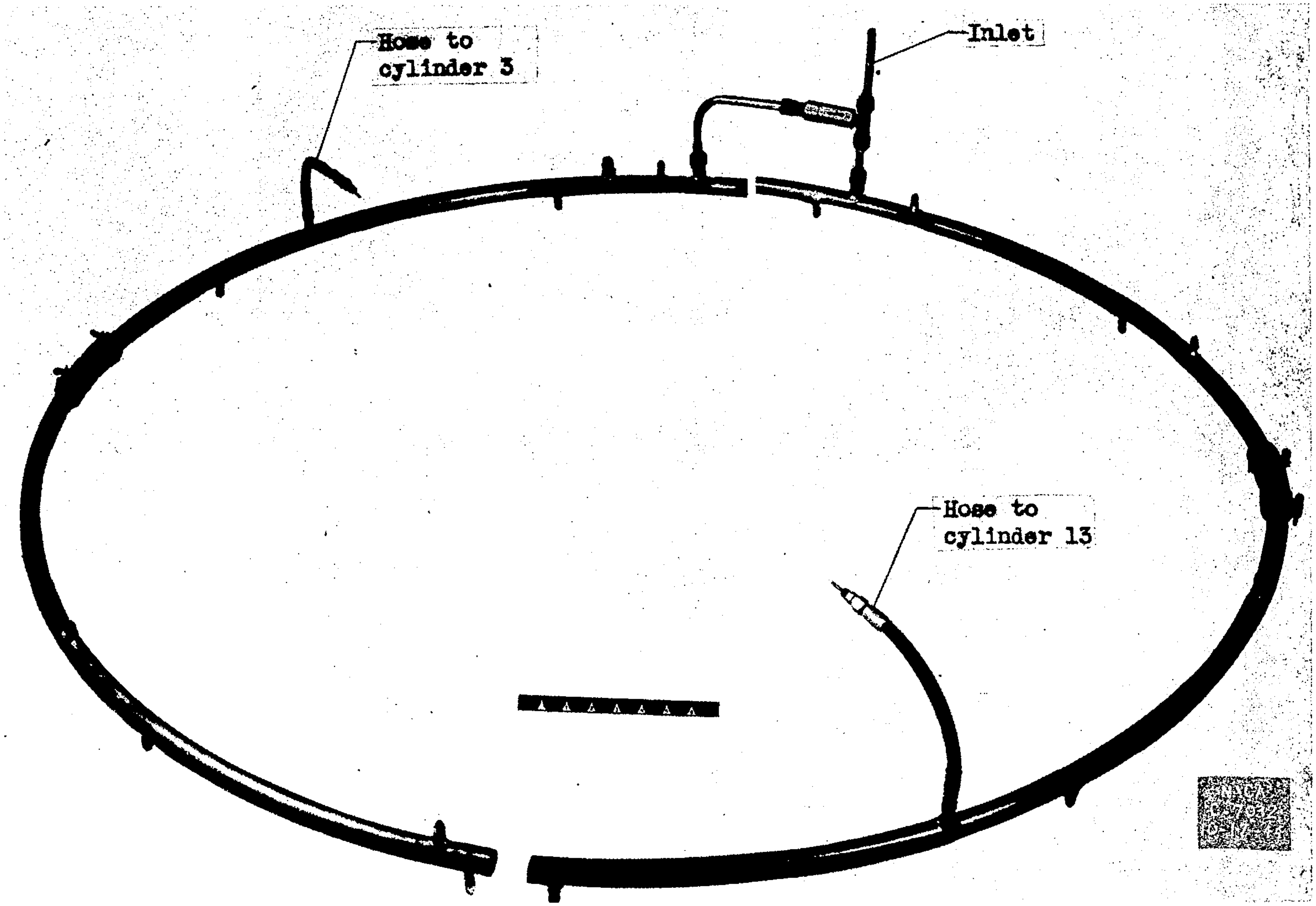


Figure 6. - Circular water-distribution manifold in double-row radial engine.

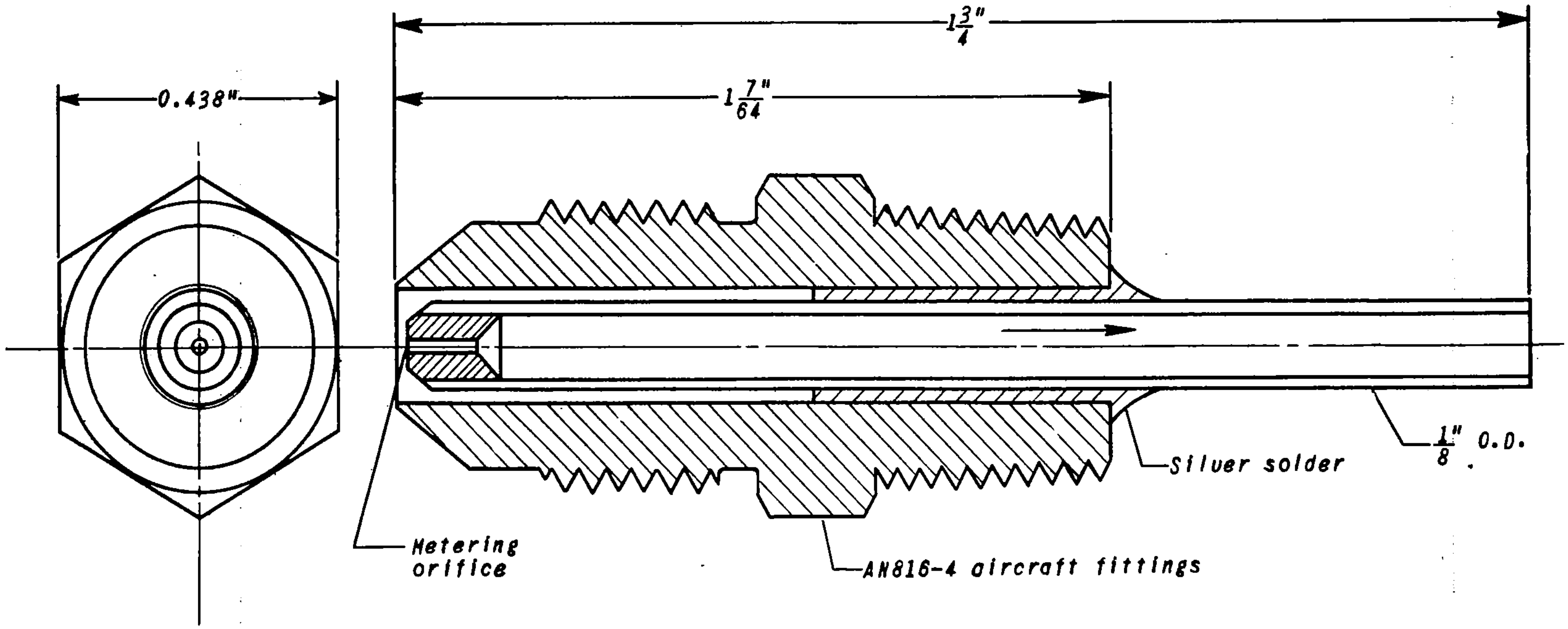


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Figure 7. - Sketch of injection nozzle used in water-injection tests of double-row radial engine in bomber power-plant installation.

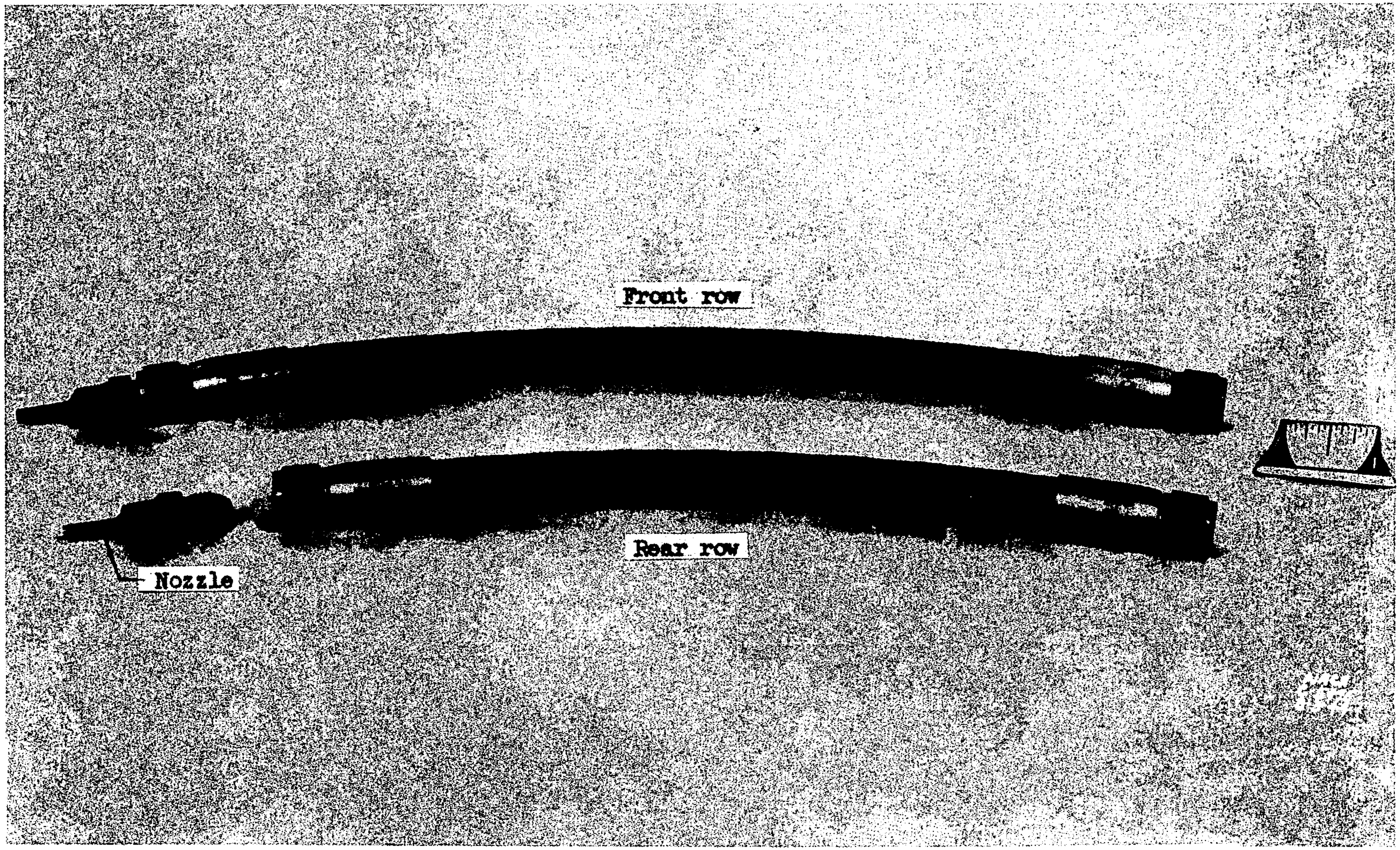

Figure 8. - Hose and injection-nozzle assemblies for double-row radial engine.

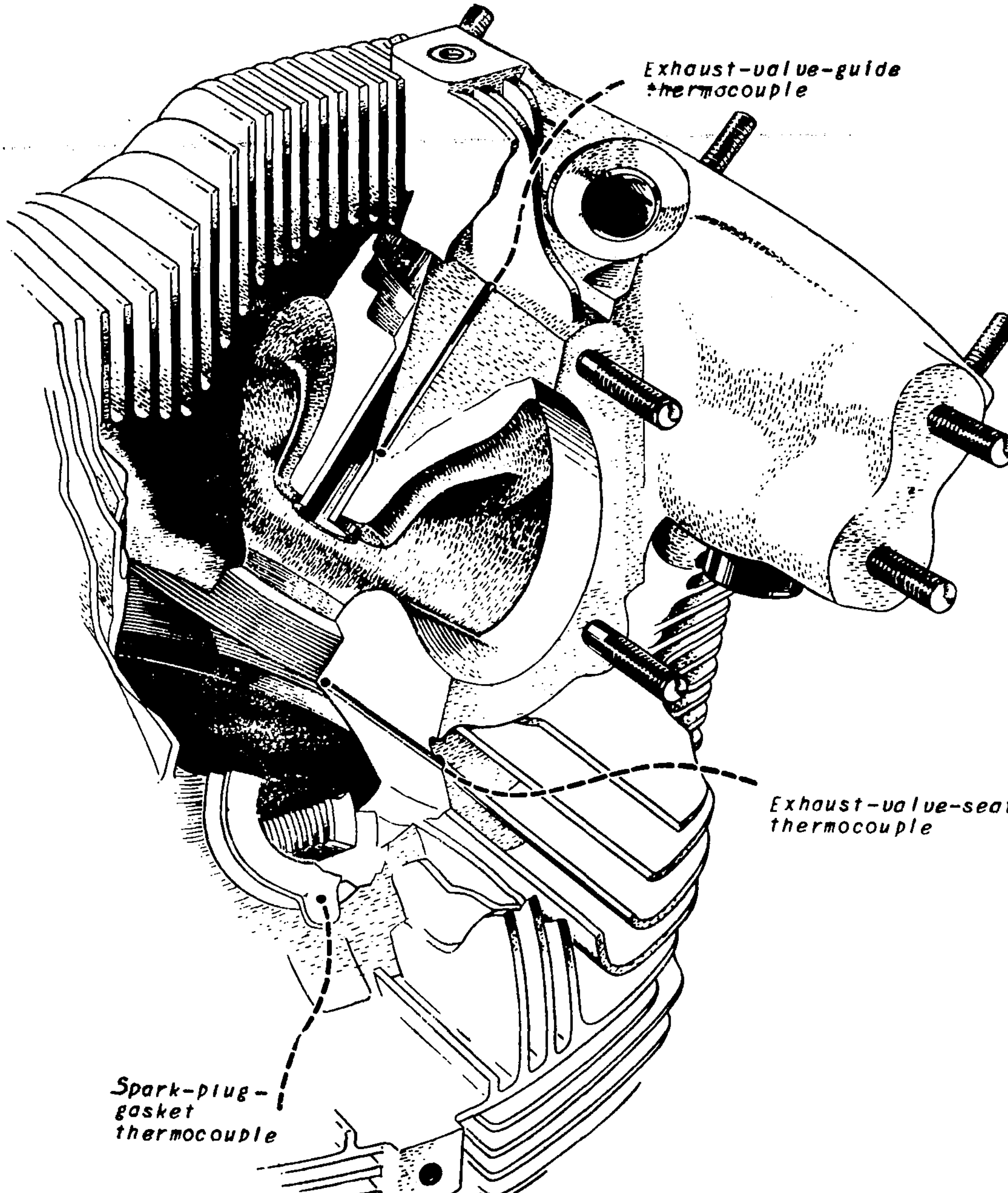

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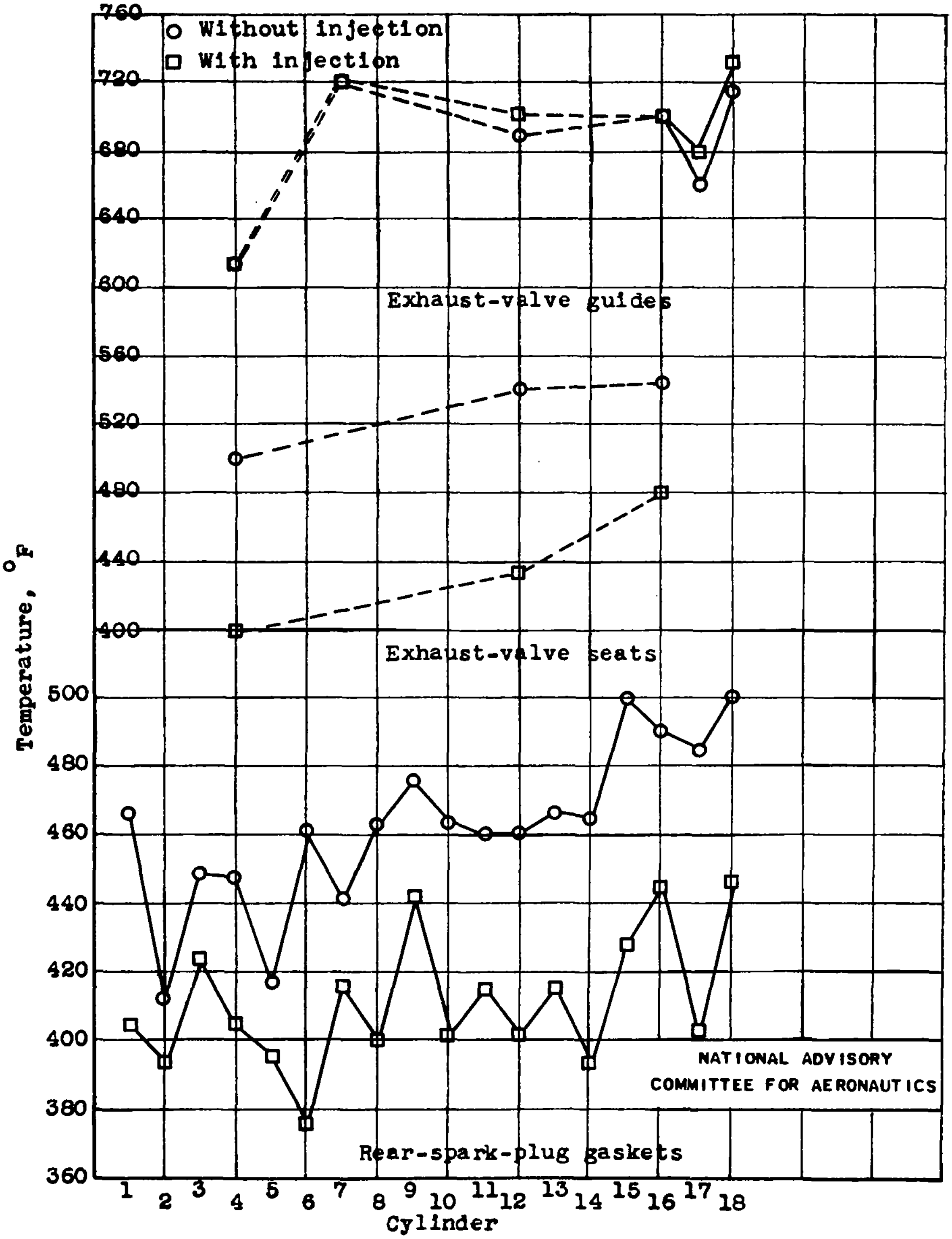
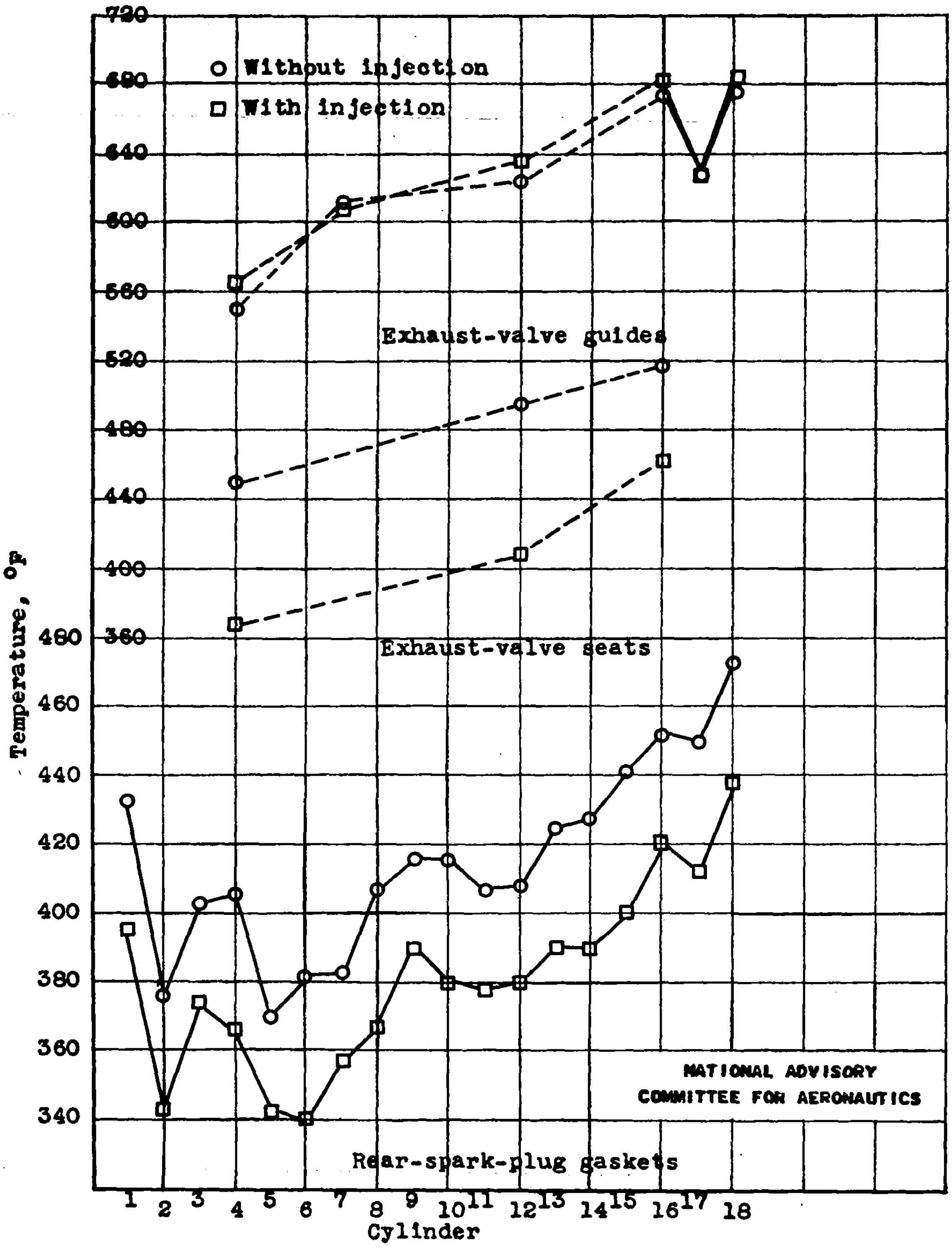
Figure 9. - Location of cylinder-head thermocouples installed in double-row radial engine cylinder.



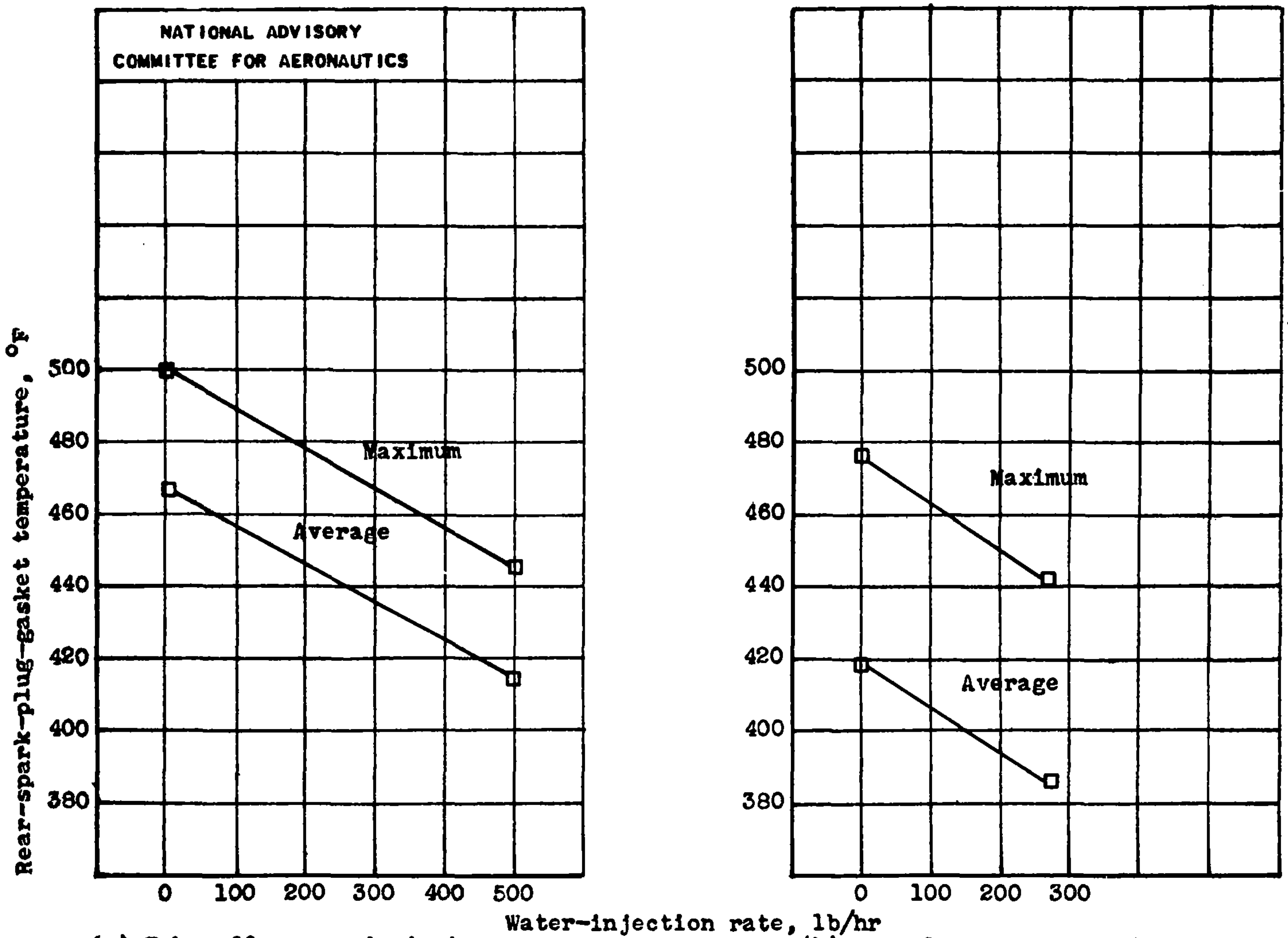
(a) Take-off power: brake horsepower, 2200; engine speed, 2600 rpm; injection rate, 500 pounds per hour.

Figure 10. - Effect of NACA individual-cylinder water injection on cylinder-head temperatures in wind-tunnel tests of double-row radial engine. (Dashed lines between data points indicate that temperature measurements were not taken on the intervening cylinders.)



(b) Normal rated power: brake horsepower, 2000; engine speed, 2400 rpm; injection rate, 285 pounds per hour.

Figure 10. - Concluded.



(a) Take-off power: brake horsepower, 2200; engine speed, 2600 rpm.

(b) Normal rated power: brake horsepower, 2000; engine speed, 2400 rpm.

Figure 11. - Effect of NACA individual-cylinder water injection on the average and maximum rear-spark-plug-gasket temperatures during wind-tunnel tests of double-row radial engine at take-off and normal rated powers.

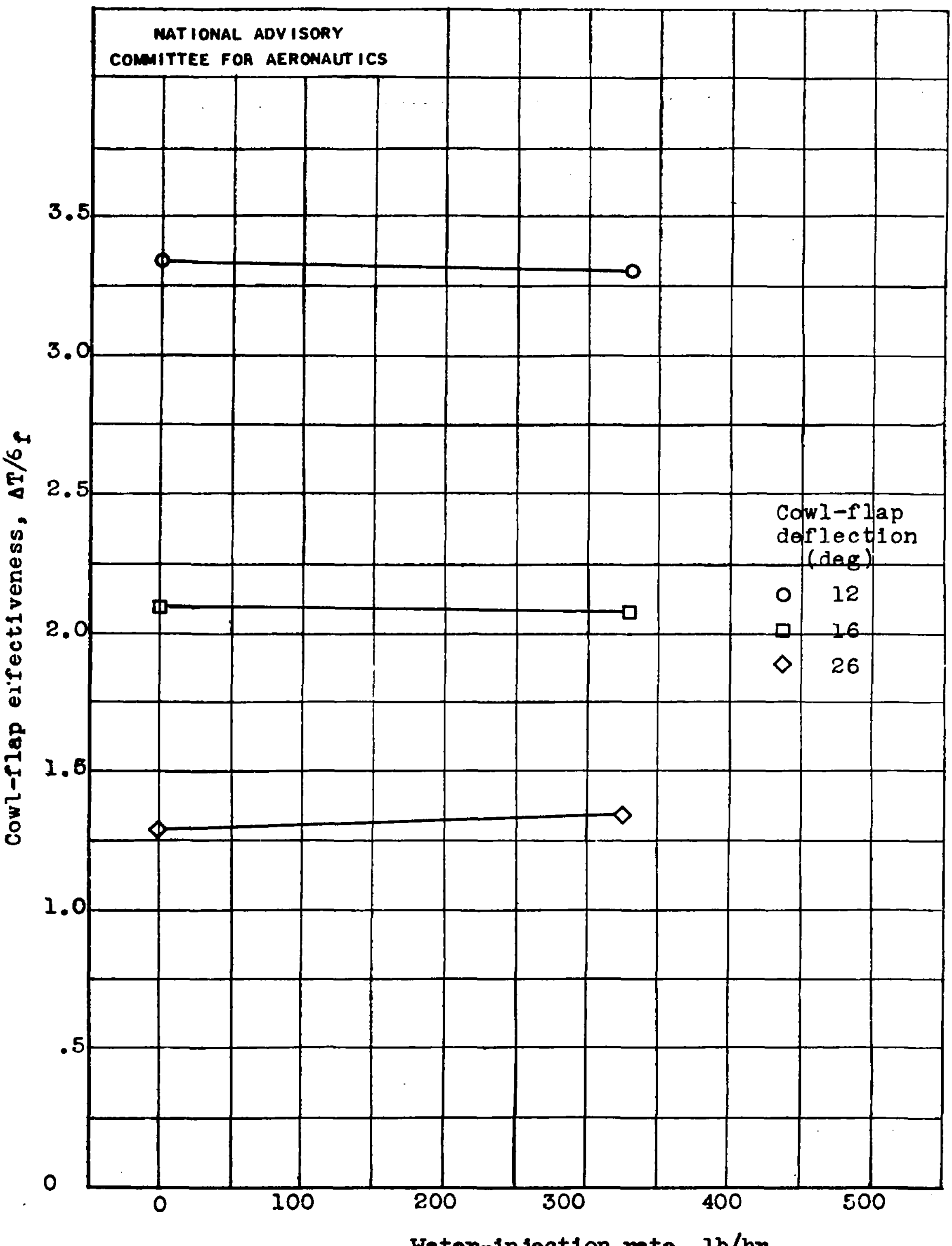


Figure 12. - Effect of NACA individual-cylinder water injection on cowl-flap effectiveness during wind-tunnel tests of double-row radial engine at take-off power. Brake horsepower, 2200; engine speed, 2600 rpm.

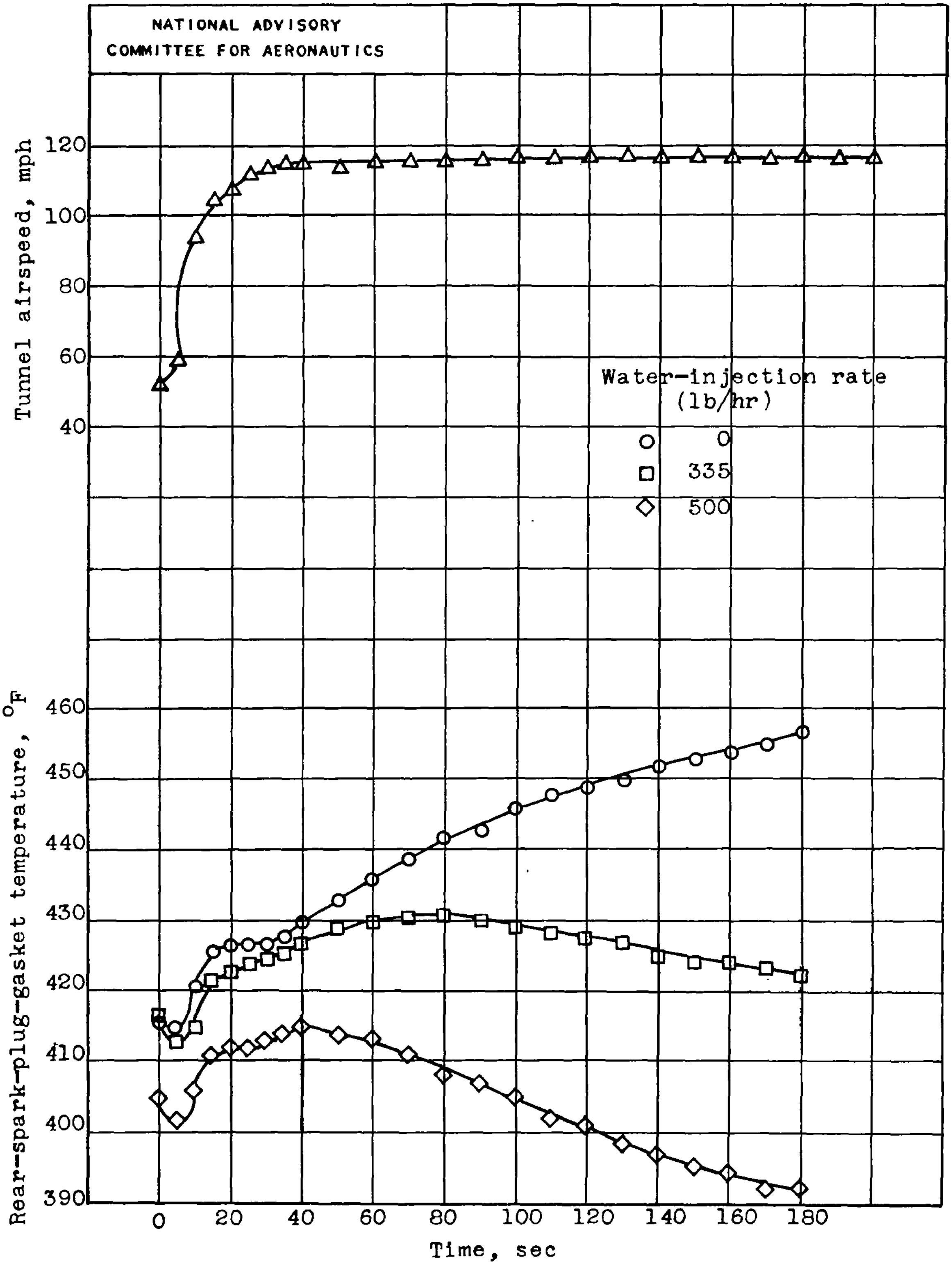
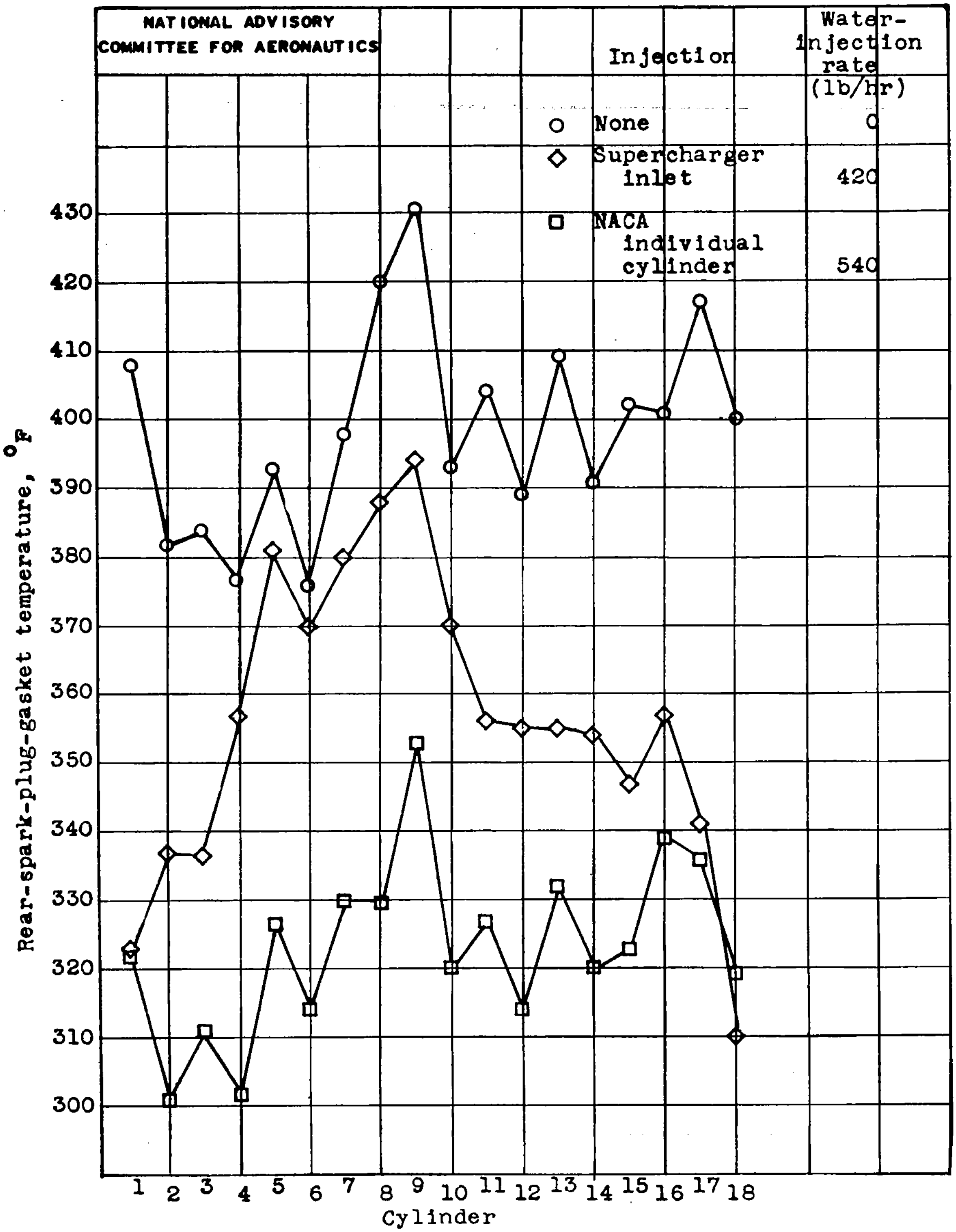
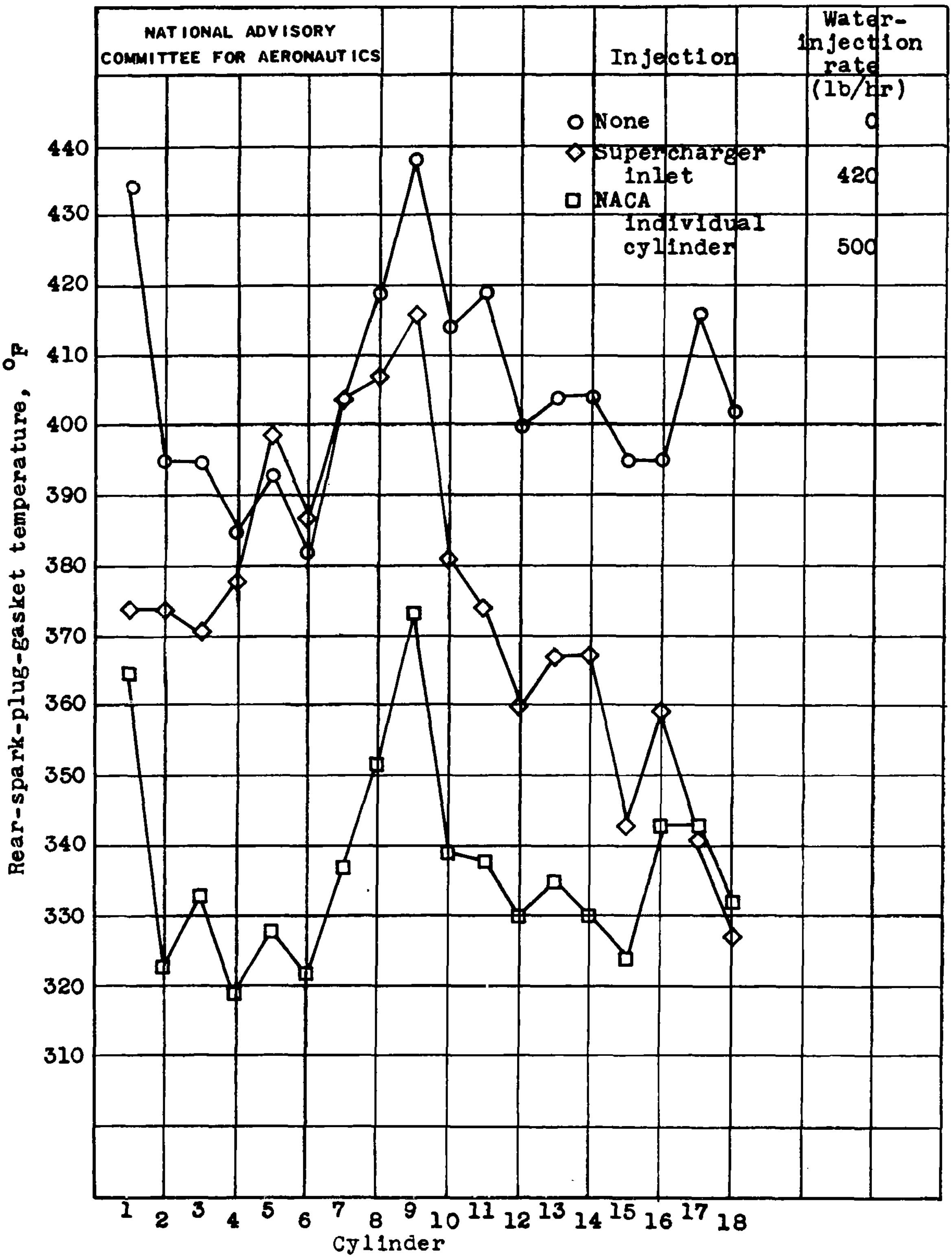


Figure 13. - Effect of NACA individual-cylinder water injection on rear-spark-plug-gasket temperatures during wind-tunnel tests of double-row radial engine at simulated take-off. Brake horsepower, 2200; engine speed, 2600 rpm.



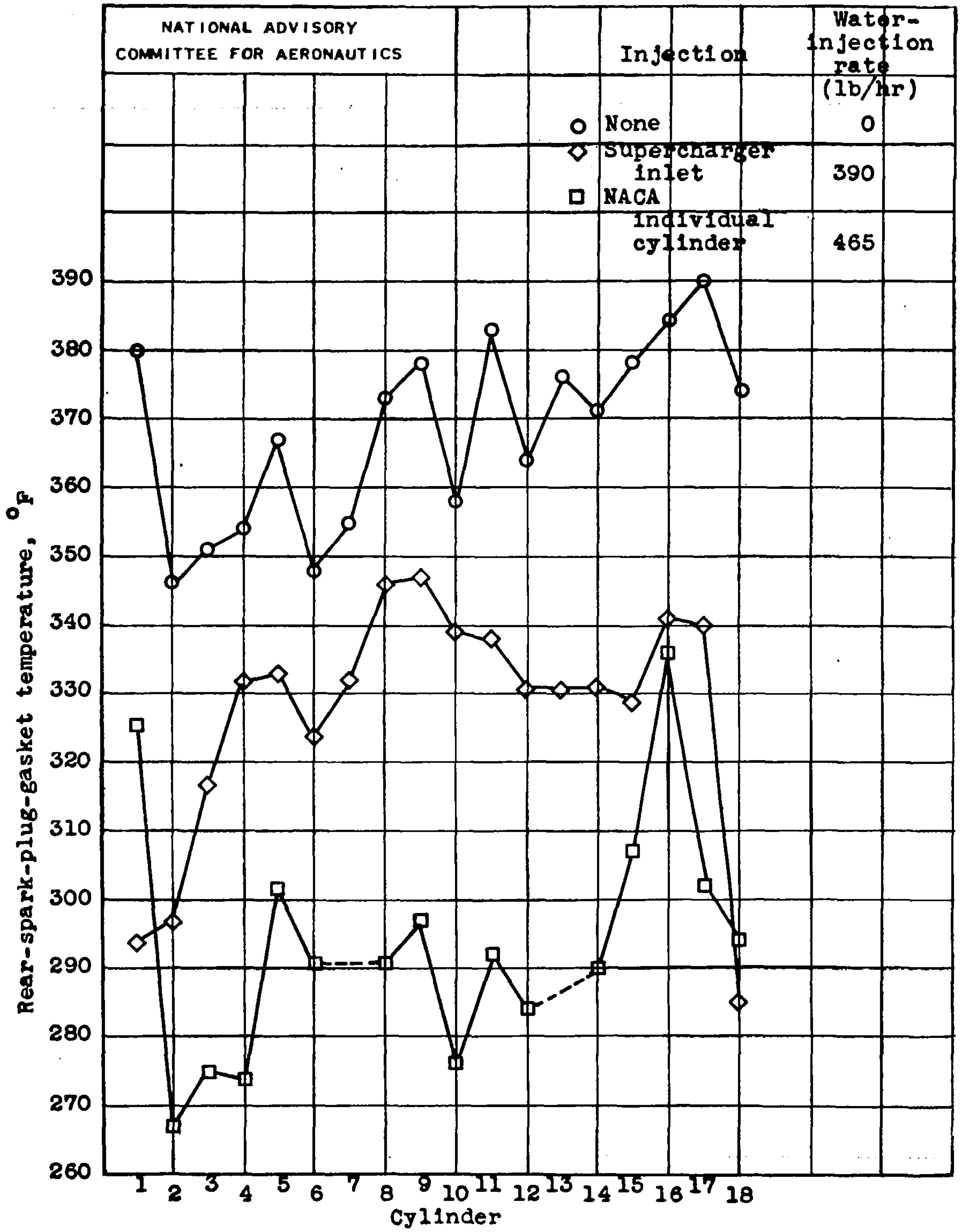
(a) Take-off power: approximate brake horsepower, 2200; approximate engine speed, 2600 rpm.

Figure 14. - Effect of NACA individual-cylinder water injection and supercharger-inlet injection on rear-spark-plug-gasket temperatures during flight tests of double-row radial engine.



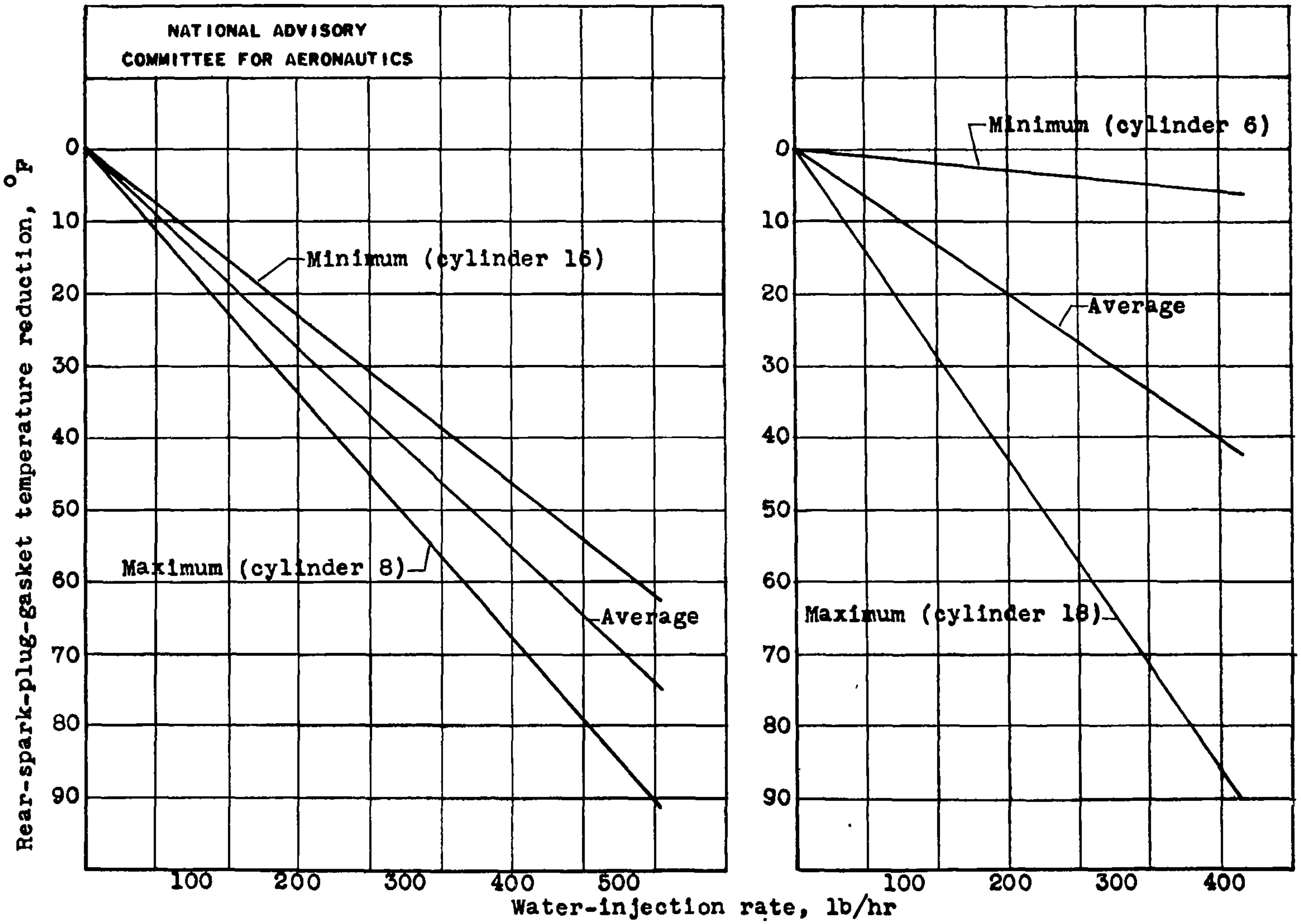
(b) Take-off power: approximate brake horsepower, 2200; approximate engine speed, 2800 rpm.

Figure 14. - Continued.



(c) Normal rated power: approximate brake horsepower, 2000; approximate engine speed, 2400 rpm. (Dashed lines between data points indicate that the injection nozzles in the intervening cylinders were plugged.)

Figure 14. - Concluded.

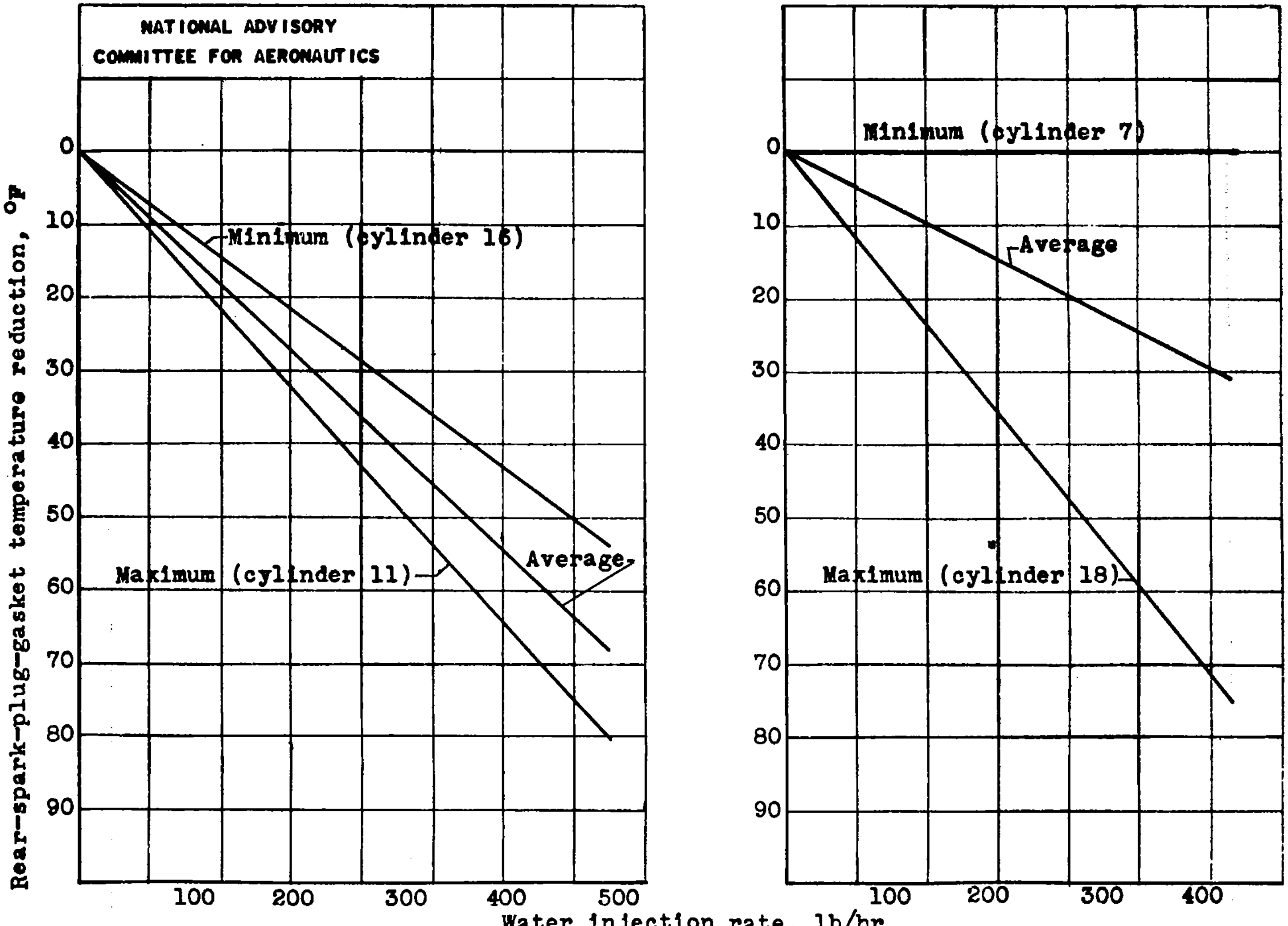


NACA individual-cylinder injection.

Supercharger-inlet injection.

(a) Take-off power: brake horsepower, 2200; engine speed, 2600 rpm.

Figure 15. - Variations of the maximum, average, and minimum rear-spark-plug-gasket temperature reductions with two water-injection systems during flight tests of double-row radial

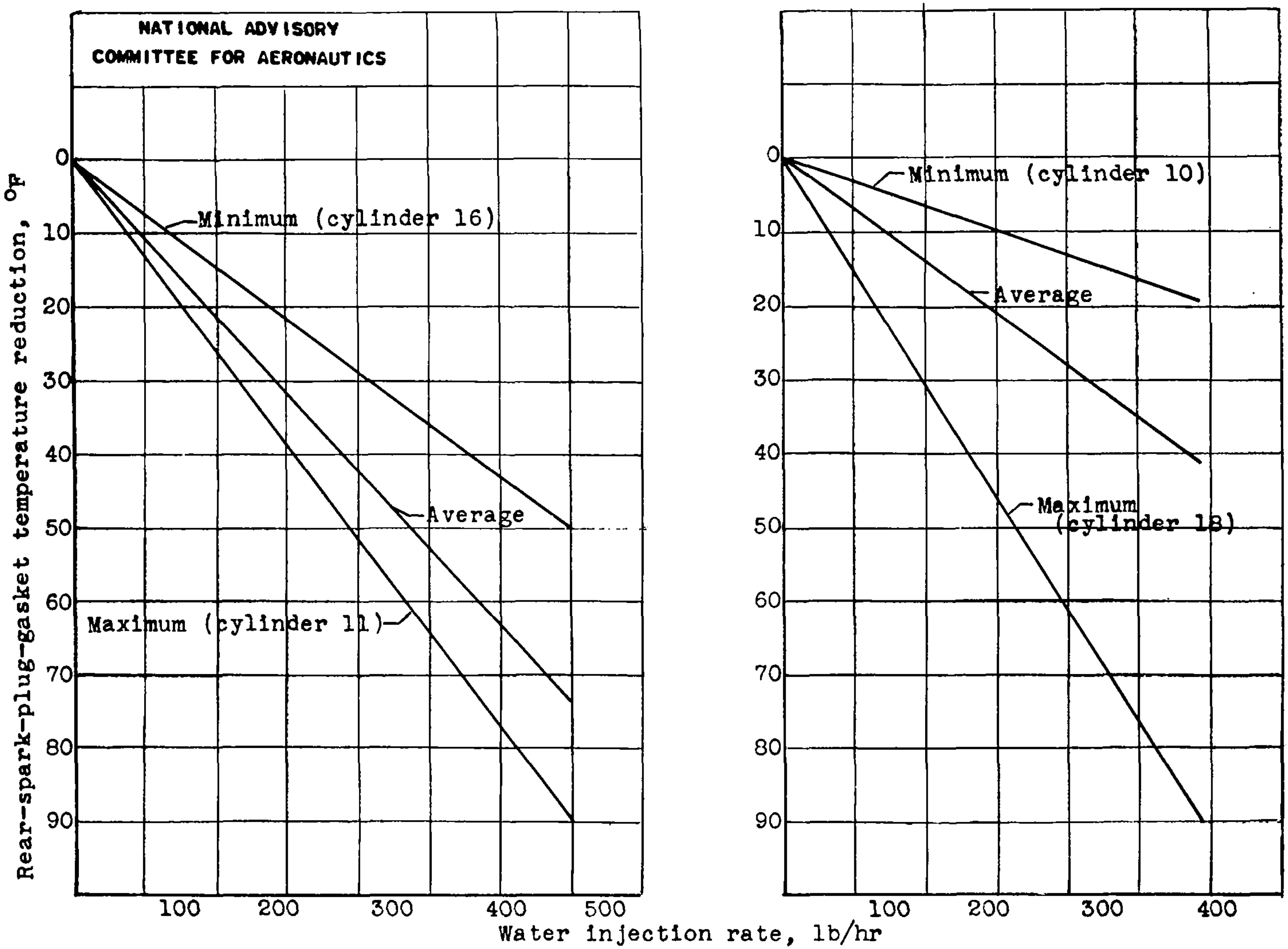


NACA individual-cylinder injection.

Supercharger-inlet injection.

(b) Take-off power: brake horsepower, 2200; engine speed, 2800 rpm.

Figure 15. - Continued.



NACA individual-cylinder injection. Supercharger-inlet injection.

(c) Normal rated power: brake horsepower, 2000; engine speed, 2400 rpm.

Figure 15. - Concluded.

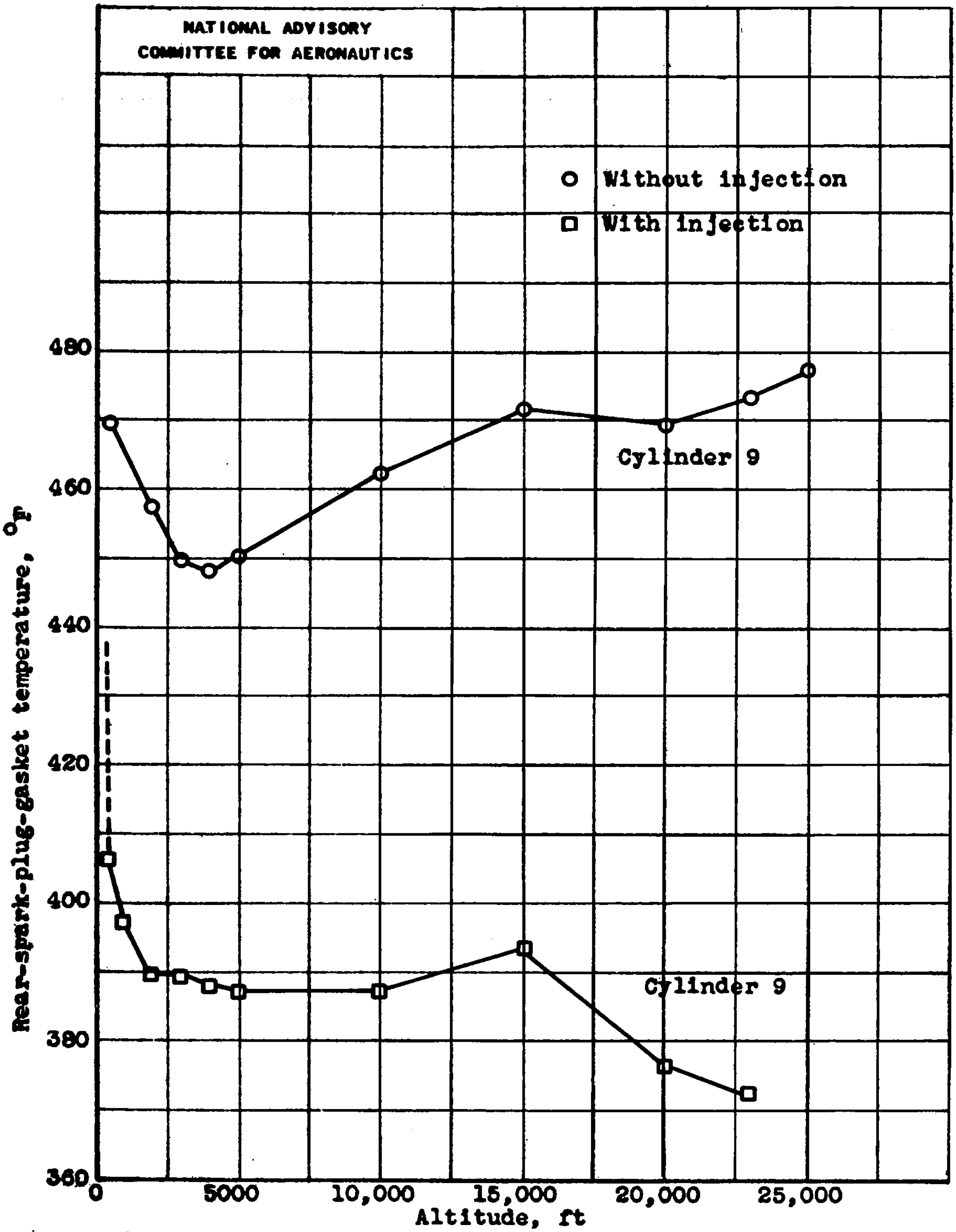


Figure 16. - Effect of NACA individual-cylinder water injection on maximum rear-spark-plug-gasket temperatures during take-off and climb flight test of double-row radial engine. Brake horsepower, 2200; engine speed, 2800 rpm; indicated airspeed, 205 miles per hour.

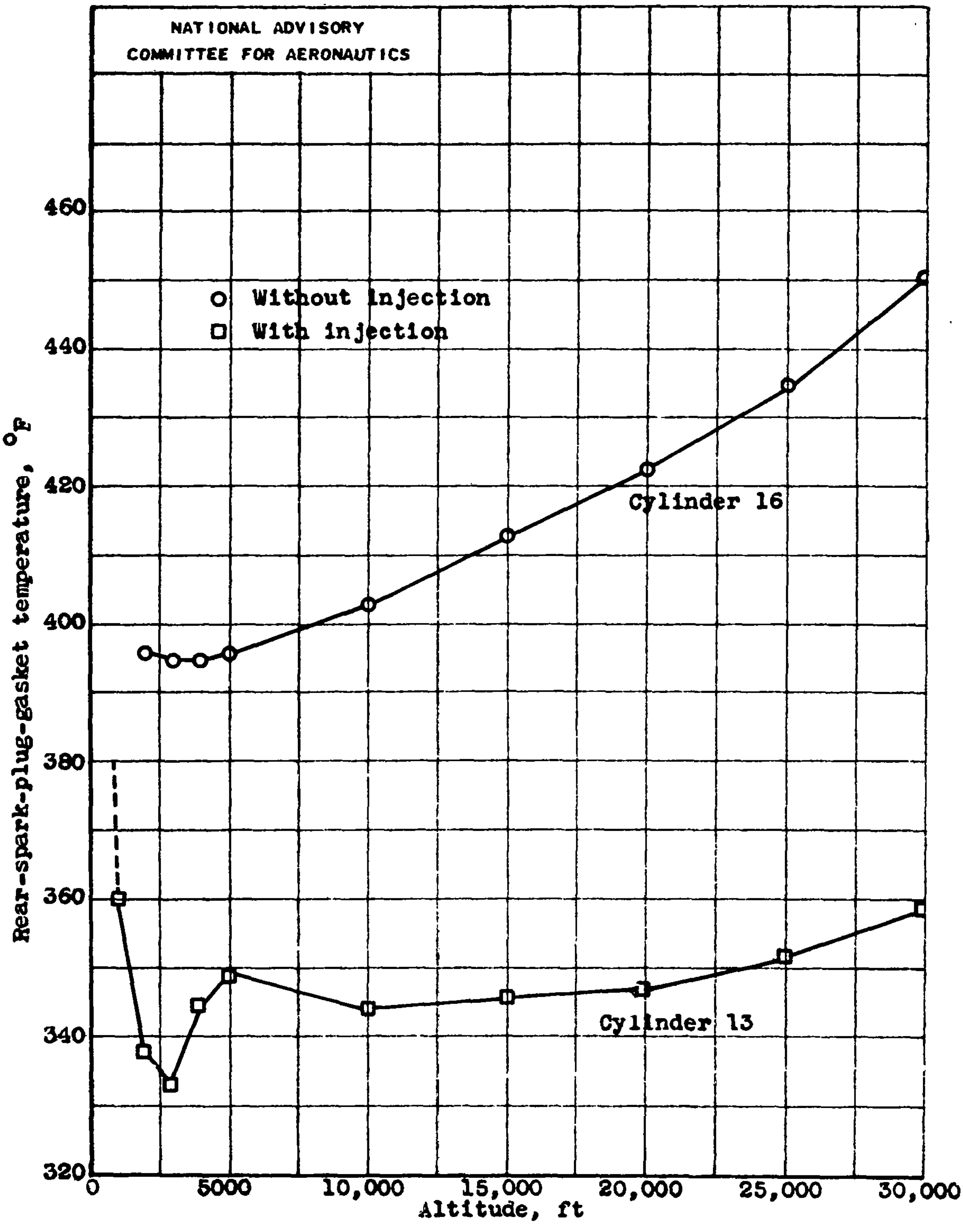


Figure 17. - Effect of NACA individual-cylinder water injection on maximum rear-spark-plug-gasket temperature during take-off and climb flight test of double-row radial engine. Take-off: brake horsepower, 2200; engine speed, 2800 rpm; climb: brake horsepower, 2000; engine speed, 2400 rpm; indicated airspeed, 205 miles per hour.